THE ASIAN MONSOON: INTERDECADAL VARIABILITY

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1. Introduction

Prediction of the seasonal mean monsoon at least one season in advance is one of the most important problems in tropical climate. However, it also happens to be one of most difficult problem. The Asian monsoon climate exhibits variability in a variety of time scales. The predictability of the seasonal mean monsoon depends on the nature of the interannual variability (IAV) of the monsoon. Extensive studies on IAV of different components of the Asian monsoon have led to better documentation and better understanding of physical mechanisms responsible for IAV of the monsoon. Various components of the Asian monsoon also exhibit significant interdecadal variability (Mooley and Parthasarathy, 1984; Kripalani *et al.*, 1997; Mehta and Lau, 1997; Chang *et al.*, 2001b, 2000; Parthasarathy *et al.*, 1991; Wu and Wang, 2002). Modulation of IAV by the interdecadal variability influences predictability of the seasonal mean monsoon. One example of role of interdecadal variability on the predictability of the summer monsoon is seen in the change in usefulness of several predictors used in statistical prediction of the Indian summer monsoon precipitation (Gowarikar *et al.*, 1989, 1991; Thapliyal and Rajeevan, 2003). The correlation between several of these predictors and the Indian summer monsoon precipitation has been found to undergo interdecadal variations (Kumar *et al.*, 1999; Krishnamurthy and Goswami, 2000) forcing the India Meteorological Department to drop many of the original predictors in their recent statistical model (Rajeevan *et al.*, 2004). A better understanding of the interdecadal variability may, therefore, be very important in improving the predictability of the seasonal monsoon climate. However, the space-time structure of the monsoon interdecadal variability is less well documented than the IAV and mechanisms responsible for it are poorly understood. This problem is largely related to the lack of availability of good quality data for a sufficiently long period. While the instrumented record of surface climate (e.g. temperature, surface pressure and precipitation) could be extended to about 150 years, upper air data is available for only about 50 years. In this review, we shall attempt to highlight the temporal and spatial characteristics of the surface climate associated with the dominant interdecadal variability of the Asian monsoon making use of long records of rainfall, sea surface temperature (SST) and sea level pressure (SLP). Further, we shall endeavor to unravel the three dimensional structure of the dominant mode of interdecadal variability from available upper air circulation data. Connections between interdecadal variability of the monsoon and that of other climate regimes around the globe will be established and indicated that the monsoon interdecadal variability may be manifestations of a global coupled ocean-atmosphere mode of interdecadal variability. A positive feedback mechanism involving air-sea interaction will be proposed for intensification of the oscillation. An attempt will be made to understand the observed relationship between the Indian monsoon and El Nino and Southern Oscillation (ENSO) on interdecadal time scale within the context of the global three dimensional structure of the dominant mode of monsoon interdecadal variability.

2. Interdecadal Variability of the South Asian Summer Monsoon

Based on the availability of long records of reliable rainfall observation over the Indian continent, epochal variation of Indian summer monsoon rainfall has been noted previously (e.g. Mooley and Parthasarathy (1984); Parthasarathy *et al.* (1991)). Normalized anomalies of June-September (JJAS) rainfall over all India (AIR), homogeneous Indian region (HMR) and west-central Indian region (WCR) between 1871 and 2000 are shown in Figs.1a,b, and c respectively (bars). Normalized JJAS SST anomaly in the Nino3 region (150 W-90 W, 5 S-5 N) is also shown in Fig.1d. The solid curve in each figure represents normalized 11-year running mean of each variable. Standard deviation of IAV as well as that of the running mean are also noted in each figure. All three indices of Indian summer monsoon rainfall lack a trend or a climate change signal but contain coherent multidecadal variability with approximate periodicity of 55-60 years. The tri-decades between 1871 and 1900 and between 1930 and 1960 generally saw more above normal than below normal rainfall over the country. Frequency of occurrence of large scale floods were also higher during these periods. Similarly, the tri-decades between 1901 and 1930 and between 1971 and 2000 saw more below normal than above normal rainfall over the country. These periods were also characterized by higher frequency of droughts. The eastern equatorial Pacific SST (Nino3) also shows a similar interdecadal variability but is approximately out of phase with that of the summer monsoon rainfall. High correlations between the interdecadal component of variability of the three summer monsoon indices as well with that of Nino3 SST are shown in Table-1. Such epochal behavior of Indian summer monsoon rainfall with multi-decadal quasi-periodicity have been noted in many studies (Parthasarathy *et al.*, 1994; Kripalani *et al.*, 1997; Kripalani and Kulkarni, 1997; Mehta and Lau, 1997; Krishnamurthy and Goswami, 2000; Torrence and Webster, 1999).

Table 1: Correlations between LP filtered JJAS indices

CORR	AIR	HOM	WCI	NINO3
AIR	1.0			
HOM	0.96	1.0		
WCI	0.95	0.96	1.0	
NINO3	-0.77	-0.76	-0.77	1.0

In order to explore the spatial coherence of the interdecadal variability of summer monsoon rainfall, composite of JJAS precipitation anomalies over 29 meteorological subdivisions over the Indian continent during a below normal epoch (1900-1925) and an above normal epoch (1940-1965) were constructed (Fig.2a and 2b). The anomalies were calculated with respect to means of individual subdivisions. The rainfall tends to be above (below) normal over most of the country during these above (below) normal interdecadal epochs indicating a large spatial scale for the interdecadal variability of the Indian summer monsoon rainfall. The rainfall over the easternmost part and the southern tip of the country tend to go out of phase with the rest of the country. It is interesting to note that the spatial pattern of the interdecadal variability of rainfall over the Indian continent has similarity with the dominant pattern of IAV over India (Shukla, 1987; Krishnamurthy and Shukla, 2001).

The annual mean of daily mean surface temperature as well as that of daily maximum surface temperature over India are known to have a trend representing the climate change signal while the daily minimum surface temperature over India does not show such a trend (Rupakumar *et al.*, 1994). As the interdecadal variability of summer monsoon precipitation has a large continental scale, it is likely to influence the summer mean surface temperature averaged over Indian continent. During the wet (dry) interdecadal phase of the Indian summer monsoon rainfall , increased (decreased) cloudiness and evaporative cooling of the surface is expected to lead to day maximum temperature to be cooler (warmer) than normal. Increased cloudiness and enhanced moisture content in the atmosphere during the same phase is expected to result in reduced long wave cooling during the night and lead to a higher than mean minimum temperature. Using available data between 1901 and 1990, the interdecadal variability of the summer season (JJAS) mean maximum and minimum surface temperature was examined. It was found that they do have a trend. However, after detrending them using a simple least square linear fit, both minimum and maximum temperature show significant interdecadal variability (after passing through a 11-year running mean) similar to that of AIR (Fig.3). It is noteworthy that the interdecadal variation of the maximum summer surface temperature is coherently negatively correlated ($r = -0.88$) with that of the AIR. The interdecadal variation of summer minimum surface temperature is positively correlated with that of AIR after about 1930. The existence of similar interdecadal variability in the maximum and minimum surface temperature and consistency between the precipitation and surface temperature indicates a certain amount of robustness for the quasi-60 year interdecadal mode. The quasi-60 year oscillation of the Indian summer monsoon system is evident in many other parameters as well. Agnihotri *et al.* (2002) analyzed a sediment core in the eastern Arabian Sea dating back to 1200 years and found an approximate 60 year periodicity in several parameters related to surface productivity such as organic carbon (Corg) , N and Al, which in turn are related to the strength of the southwest monsoon winds. All these observations indicate that the quasi-60 year oscillation may be an intrinsic mode of oscillation of the monsoon system. El Nino and Southern Oscillation (ENSO)-like interdecadal variability of Pacific SST has been noted in several recent studies (Zhang *et al.*, 1997; Kachi and Nitta, 1997; Graham, 1994; Tanimoto *et al.*, 1993; Graham *et al.*, 1994; Kawamura, 1994). The close association between the interdecadal variability of the summer monsoon and Nino3 (Fig.1) indicates a strong link between interdecadal variability of Pacific SST and that of the Indian summer monsoon. The IAV of both the Indian monsoon rainfall as well as that of the ENSO seems to be coherently modulated by the interdecadal variability. Interdecadal variability of the interannual variance of AIR and Nino3 SST were calculated using a 21-year moving window (Fig.4). IAV of both the Indian monsoon and the ENSO also show a quasi-60 year interdecadal fluctuation. Strong correlation ($r = 0.82$) between the two indicates that the quasi-60 year oscillation is a global mode of variability that modulates activity of both the Indian monsoon and the ENSO. Similar interdecadal variability of variance in the 2-7 year band of AIR and Nino3 SSTA and the coherence between the two variabilities have also been noted by Torrence and Webster (1999). Here, we contrast the strong negative relationship between the interdecadal variability of the Indian summer monsoon and the ENSO with the ENSO-monsoon relationship on interannual time scale. The ENSO-monsoon relationship on interannual time scale has been studied extensively (Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Shukla and Paolino, 1983; Parthasarathy and Pant, 1985; Shukla, 1987; Goswami, 1998; Lau and Wu, 2001; Lau and Nath, 2000). The simultaneous correlation between JJAS Nino3 SST anomaly and AIR has remained significantly negative over a long period of time (Fig.5a). However, it has decreased sharply over the last two decades and is currently insignificantly small (Fig.5a). Another aspect of this relationship is that even when correlation was strong (e.g. between 1871 and 1971), largest correlation between AIR and Nino3 SST occurred with Nino3 SST following the monsoon season (Fig.5b). This observation prompted a hypothesis that the large scale circulation changes associated with the Indian monsoon may play an important role in determining the evolution and strength of the ENSO on interannual time scale (e.g. Nigam (1994); Kirtman and Shukla (1997)). During the recent decades, however, the largest correlation between the Indian summer monsoon rainfall and eastern Pacific SST takes place not with SST following the monsoon but with SST one year prior to the Indian monsoon (Fig.5b). This indicates a qualitative change in the ENSO-monsoon relationship during the recent years. The fact that the relationship between Indian summer monsoon and ENSO has the same sign on interannual (over a large fraction of historical data) as well as on interdecadal time scale indicates that the mechanism through which the two interact may be similar on both the time scales. The physical linkage between the two on interdecadal time scale will be examined later in the article and compared with that between the two on interannual time scale. The rapid weakening of the ENSO-monsoon relationship on interannual time scale during the recent decades has also been a subject of considerable attention (Kumar *et al.*, 1999; Krishnamurthy and Goswami, 2000; Chang *et al.*, 2001a; Torrence and Webster, 1998). It will be explored whether the changing relationship between the ENSO and Indian monsoon could be understood in terms of modulation of the ENSO-monsoon relationship on interannual time scale by the large scale circulation changes associated with the interdecadal variability.

3. Interdecadal Variability of the East Asian Summer Monsoon

The east Asian summer monsoon (EASM) encompasses both tropics and subtropics. It is distinct from the south Asian (Indian) monsoon and has complex space-time structure ranging from tropical baroclinic systems to middle latitude barotropic systems. The EASM also experiences a quasibiennial tendency on interannual time scale (Shen and Lau, 1995) like the south Asian monsoon. However, the EASM is influenced by ENSO in a distinctly different way than the south Asian monsoon. While the Indian summer monsoon precipitation correlates strongly with eastern Pacific SST during the evolving phase of the ENSO (Fig.5b), the EASM correlates strongly with eastern Pacific SST during the decaying phase of the ENSO (Shen and Lau, 1995; Chang *et al.*, 2001b, 2000; Wang *et al.*, 2001; Wu and Wang, 2002). The EASM also exhibit interdecadal variability somewhat similar to that observed in the Indian monsoon rainfall. In order to get an idea of temporal scale of the interdecadal variability of the EASM, May-August (MJJA) precipitation over two regions for the period between 1901 and 1998 were extracted from historical rainfall records compiled by Dr. Mike Hulme of University of East Angelia, U.K (Hulme *et al.*, 1998). The climatological precipitation during MJJA over the east China around the Yangtze River Valley (27.5°N-37.5°N, 100°E-122.5°E) and over north-eastern China (37.5°N-47.5°N, 115°E-125.5°E) are 56 cm and 40.4 cm respectively. The interannual and interdecadal (11 year running mean of interannual anomalies) variations normalized by their own standard deviations are shown in Fig.6. A quasi 50-60 year interdecadal periodicity is evident in both time series similar to that observed in the south Asian monsoon rainfall (Fig.1a,b,c). Roughly after 1920, the phase of the interdecadal variability of the EASM precipitation also has similarity with that of the south Asian summer monsoon. It is noteworthy here that a 65-70 year periodicity of the global temperature record was found by Schlesinger and Ramankutty (1994) after removing the trend. Thus, the quasi-60 year oscillation in both south Asian summer monsoon and the EASM may be manifestation of a global mode of interdecadal variability. The EASM goes through a major interdecadal transition in the mid-seventies concurrent with the major climatic transition in the tropical Pacific. While this is clearly seen in the east China precipitation (Fig.6a), the complex spatial structure associated with this interdecadal transition influences the whole EASM region. The spatial structure and possible causative mechanisms for this interdecadal transition of the EASM has been examined in several studies (Hu, 1997; Wu and Wang, 2002; Chang *et al.*, 2001b, 2000) using station rainfall data over China, Japan and Korea and NCEP/NCAR reanalysis. A negative-positive-negative precipitation pattern over the southeastern China, Yangtze River Valley and northeastern China during the pre-transition (1962-1977) period seems to go over to a positive-negative-positive pattern during the post-transition (1978-1993) period (Wu and Wang, 2002). Significant interdecadal changes of large scale circulation are also found consistent with the interdecadal changes in precipitation pattern. The low level anticyclone is stronger and located at higher latitudes in 1978-1993 than in 1962-1977. Also the barotropic anticyclonic anomaly over the Japan sea during the earlier epoch turned into cyclonic during the later epoch. The circulation over the EASM region could be influenced by western north Pacific convection through low level response and by the Indian summer monsoon heating through upper level wave response. It appears that during 1978-93, the western north Pacific convection was largely responsible for the interdecadal anomalies while during the earlier epoch both processes contributed to it (Wu and Wang, 2002). Significant change in summer time typhoon tracks were also found by Ho *et al.* (2004) between two interdecadal periods, namely between 1951-1979 and 1980-2001 consistent with the westward and northward extension of the subtropical northwestern Pacific high.

4. Mechanism for Interdecadal Variability of Enso-Monsoon Relationship

A framework is described here that may be used as a basis through which we may attempt to understand the observed interdecadal variability. The mean summer precipitation has a primary maximum in the monsoon trough (MT) region between 15°N and 25°N with a secondary maximum in the equatorial Indian Ocean. Low level cyclonic vorticity, arising through interaction of low level converging flow with the Himalayan mountain range, helps organized convection through frictional moisture convergence and makes the MT a preferred location of the tropical convergence zone (TCZ). The eastern equatorial Indian Ocean with a maximum of SST between equator and 10 S during the summer season represents another preferred location of the TCZ (Goswami and Shukla, 1984). Within the summer monsoon season, vigorous intraseasonal oscillations (ISOs) in the form of active/break cycles ride on the seasonal mean monsoon. The ISOs are characterized by a competition of the TCZ to fluctuate between the two preferred locations with repeated northward propagation from the equatorial position to the MT (Yasunari, 1979; Sikka and Gadgil, 1980). The seasonal mean precipitation is influenced by statistical average of the ISOs of the TCZ over the season (Goswami and Ajayamohan, 2001a). Thus, processes that influence the frequency of occurrence of the TCZ over the equatorial IO preferred region could influence the seasonal mean monsoon Hadley circulation and seasonal mean monsoon precipitation. The strength and distribution of SST over the equatorial IO as well as the convergences and divergences associated with the equatorial Walker circulation could influence the equatorial ISOs and thereby influence the seasonal mean monsoon precipitation (Chandrasekar and Kitoh, 1998; Krishnan *et al.*, 2003). Therefore, link between the Pacific SST and that of the Indian monsoon rainfall could be expected through modification of the equatorial Walker circulation and the regional monsoon Hadley circulation. In order to bring out the robust global patterns of SST and SLP associated with the interdecadal variability of the Indian summer monsoon as well as with that of the ENSO, long records of AIR, SST and SLP since 1871 are used. The spatial pattern associated with interdecadal variability of Indian summer monsoon is obtained by regressing global SST and SLP fields on the low pass filtered AIR (solid curve in Fig.1a) and shown in Figs.7a and 7c respectively. Similarly, the spatial pattern associated with the interdecadal variability of ENSO is obtained by regressing the global SST and SLP field on the low pass filtered -Nino3 (negative of the solid curve in Fig.1d) and shown in Fig.7b and 7d respectively. These patterns are similar to those associated with the ENSO-like interdecadal variability noted in some earlier studies (Kachi and Nitta, 1997; Zhang *et al.*, 1997; Enfield and Mestas-Nunez, 1999). Some minor differences between patterns shown in Fig.7 and those obtained by Zhang *et al.* (1997) are due to the fact that while the patterns shown here were obtained by regressing northern hemisphere summer mean (JJAS) anomalies, their patterns were obtained by regressing monthly mean anomalies for the entire period which resulted in more weighting from northern hemispheric winter SST pattern associated with the interdecadal mode. The global spatial patterns of SST associated with interdecadal variability of AIR and ENSO (Fig.7a,b) are almost identical, the pattern correlation between the two being 0.86. Similarly the global spatial pattern of SLP associated with interdecadal variability of AIR and ENSO (Fig.7c,d) are also almost identical, the pattern correlation between the two being 0.85. A possible implication of this observation is that the interdecadal variability of monsoon and ENSO are manifestations of a global coupled ocean-atmosphere mode of interdecadal variability. It may be possible to gain some insight regarding the relationship between the ENSO and Indian monsoon on interdecadal time scale by examining the three dimensional structure of the global interdecadal mode of variability during 1948-2002 for which NCEP/NCAR reanalysis (Kalnay *et al.*, 1996) circulation data is available. Hence, a multivariate empirical orthogonal function (EOF) analysis of LP filtered SST, precipitation, winds at 850 hPa and 200 hPa and velocity potential at 200 hPa was carried out. The first EOF explaining 41.5 percent of variance of the LP filtered fields together with the corresponding principal component (PC1) are shown in Fig.8 and 9 respectively. The global SST pattern associated with the EOF1 (Fig.8a) is similar to the pattern associated with interdecadal variability of ENSO (Fig.7b) based on long data of SST (spatial correlation between the two patterns being -0.7). The time evolution of PC1 is quite similar to the LP filtered Nino3 time series (Fig.1d) during the period 1948-2002. The EOF1 essentially represents the interdecadal modulation of ENSO from a La Nina preferred regime in 1950 s and 1960 s to an El Nino preferred regime during 1980 s and 1990 s with a transition around mid 1970 s. Therefore, the three dimensional structure associated with the EOF1 may be representative of that of the interdecadal variability of the ENSO and the Indian monsoon discussed earlier with approximate period of 55-60 years. While the EOF1 explaining 41.5 per-cent of the LP filtered variance is quite distinct from the other EOFs and could be considered a natural mode of oscillation representative of the multidecadal amplitude modulation of the ENSO, the EOF2 and EOF3 explaining 10.1 percent and 9.8 percent variance of LP filtered fields are not distinct from each other and could not be considered as independent modes of oscillation. Hence, we focus our attention primarily on EOF1 representing the multidecadal component of the variability. Associated with the EOF1, the ENSO-like SST warming (cooling) of SST in the eastern tropical Pacific is in phase with SST over the tropical IO (Fig.8a). The spatial pattern of precipitation associated with interdecadal mode (Fig.8b) consists of enhancement of precipitation over two major regions namely, northern south America and eastern equatorial IO and Indonesia and decrease in precipitation over two major regions namely, central and eastern Pacific and central Africa. Consistent with the precipitation pattern, the wind patterns show low level convergence and upper level divergences over equatorial central America and northern south America and Indonesia while low level divergence is seen over equatorial eastern Africa and central Pacific around dateline (Fig.8c). A comparison between Fig.8c and Fig.9a shows that in the equatorial region, low level convergence (divergence) is always associated with upper level (200 hPa) divergence (convergence). The upper level velocity potential field of the interdecadal mode (Fig.9b) is consistent with the divergent circulation associated with the precipitation anomalies (Fig.8b). The vertical structure of the oscillation in the equatorial region is, therefore, that of a first baroclinic mode. The precipitation pattern and the equatorial circulation are indicative of a three cell Walker circulation and is consistent with the velocity potential field at 200 hPa (Fig.9b). The upper level easterly jet in the equatorial IO (Fig.9a) is weakened during the warm phase of the interdecadal variability. This is a signature of weakened Indian monsoon. To gain a better understanding of the ENSO-monsoon relationship on interdecadal time scale, a comparison of spatial structure and strength of the regional monsoon Hadley (MH) circulation and the Walker circulation associated with the interdecadal and interannual time scales is required. For an estimate of the MH and Walker circulation associated with the interdecadal time scale, a warm (1982-1995) minus cold (1952-1965) composite of LP filtered zonal and meridional winds and vertical pressure velocity were created. The LP filtered fields are slowly varying and has no seasonal variations. Therefore, all months within each period were taken in these composites. The interdecadal MH circulation is represented as pressure-latitude section of vector winds constructed with meridional wind and negative of vertical pressure velocity averaged over 70 E-110 E (Fig.10a). The interdecadal Walker circulation is represented as pressure-longitude section of vector winds constructed with zonal wind and negative of vertical pressure velocity averaged over 10 S-10 N (Fig.10b). A similar estimate of MH and Walker circulation associated with interannual ENSO mode was made by constructing a JJAS composite of El Nino minus La Nina from the interannual anomalies (after removal of the LP filtered component). 1957, 1965, 1972, 1976, 1982, 1983, 1987 and 1997 were used for El Nino composite while 1964, 1970, 1973, and 1988 were used for La Nina composite. The El Nino (La Nina) years were selected based on JJAS Nino3 SST anomaly being greater than +1 (less than -1) standard deviation. The MH and Walker circulation associated with the interannual ENSO mode are shown in Fig.11. The interdecadal MH circulation is characterized by significant deep ascending motion over the equatorial IO between 10 S and 10 N and upper level subsidence extending down to 500 hPa north of 10 N. The large scale persistent upper level subsidence inhibits convective activity over the Indian summer monsoon region leading to an overall decrease in monsoon rainfall.

This appears to be responsible for the negative correlation between interdecadal variability of the ENSO and the summer monsoon. Since the Indian winter monsoon is associated with precipitation only over the southern tip of India extending to about 12 N, the winter convection (or rainfall) is facilitated by the enhanced upward motion in this region. This is consistent with the positive correlation between the Indian winter monsoon rainfall and the ENSO on interdecadal time scale (not shown). As could be derived from the EOF1 (Fig.10), the Walker circulation associated with interdecadal variability has a three east-west cell structure with ascending motion in the eastern equatorial IO and around 60^0 W and descending motion in the eastern Pacific between dateline and 120^0 W and over central Africa. A point of some significance is to note that the anomalies of the MH and Walker circulation associated with the interdecadal and interannual ENSO variability are comparable in magnitude. During a warm eastern Pacific phase of the interdecadal mode, the upward motion associated with the MH circulation over the equatorial IO is opposed by the descending motion associated with the interannual El Nino while both the modes reinforce the descending motion over the Indian monsoon region. During the same warm phase of the interdecadal mode, the MH circulation associated with interannual La Nina would result in an enhancement of the equatorial ascending motion while compensating the the decadal descending motion over the Indian summer monsoon region. This means that during the warm interdecadal phase (e.g.1965-1995), the El Nino s are likely to have a stronger negative influence on the Indian summer monsoon while the La Nina s may not have any significant positive influence. Similarly, during a cold phase of the interdecadal mode (e.g. 1948-1965) , a La Nina is likely to have stronger positive effect on the Indian summer monsoon while the El Nino s are likely to have no significant negative influence on the summer monsoon. With the exception of 1997, this conclusion appears to be generally born out by the observed Indian summer monsoon rainfall (Fig.1, also see Kripalani and Kulkarni (1997)). During 1997, the expected negative influence on the Indian monsoon by the strong El Nino on a warm interdecadal phase of ENSO appears to have been countered by some strong regional influence of opposite sign.

5. Decadal Changes in Monsoon Intraseasonal Activity

Intraseasonal oscillations (ISOs) are an integral part of the Asian monsoon. The Indian summer monsoon is characterized by a northward propagating 30-60 day oscillation (Yasunari, 1979; Sikka and Gadgil, 1980; Goswami, 2004a) and a quasi-biweekly oscillation (Krishnamurti and Bhalme, 1976; Chen and Chen, 1993; Chatterjee and Goswami, 2004). The basic characteristics of the summer monsoon ISOs and mechanism for their genesis and scale selection have been studied extensively (for summary see Webster *et al.* (1998); Goswami (2004a)). The ISOs essentially arise from internal dynamics, namely feedback between convection and dynamics (Goswami and Shukla, 1984; Chatterjee and Goswami, 2004). As this feedback is a function of the background mean flow and thermal structure, the statistics (e.g. frequency of occurrence, amplitude etc) of monsoon ISOs may be modulated by the modulation of the large scale background flow on interdecadal time scale. Does any characteristic statistical property of the monsoon ISOs change significantly from the cold interdecadal phase of ENSO in the pre-1970 s to the warm interdecadal ENSO phase of post1970s? This question is examined here using daily NCEP/NCAR reanalysis data between 1948 and 2002. The amplitude of intraseasonal variability (ISOV) during the Indian summer monsoon season is represented by the standard deviation of the 10-90 day filtered intraseasonal anomalies between 1 June and 30 September at each grid point. The climatological mean ISOV based on all the years for zonal winds and relative vorticity at 850 hPa and vertical pressure velocity at 500 hPa over the Indian monsoon region are shown in Fig. 12. Interannual standard deviation of the ISOV of the three fields are shown in Fig.13. Existence of significant IAV of the ISOV is evident from Fig. 13 (15-20 percent of the climatological mean). The interdecadal variability of ISOV is constructed by average of interannual anomalies of standard deviation of 10-90 day filtered zonal winds at 850 hPa and relative vorticity at 850 hPa over

40°E-100°E, 10°N-35°N, through a 11-year moving window and are shown in Fig. 14 together with the PC1 of multivariate EOF of the LP filtered fields (Fig.9). The interdecadal variability of the ISOV in 500 hPa vertical velocity (not shown) is also similar to that of the other two variables shown in Fig. 13. It is interesting to note that the interdecadal variability of ISO activity over the Indian summer monsoon region has a close correspondence with the interdecadal variability of the ENSO-monsoon mode. The periods between 1955-1975 and between 1980 and 1995 were characterized by systematically higher and lower than normal ISO activity respectively over the Indian monsoon region. The transition from higher than normal to lower than normal ISO activity takes place simultaneously with that of the coupled interdecadal mode in the mid-1970 s. The correlation between the LP filtered ISOV of zonal winds and relative vorticity at 850 hPa is 0.92 while that between PC1 and the LP filtered ISOV of relative vorticity at 850 hPa is -0.73. Why does the ISOV decrease over the Indian summer monsoon region during the warm phase of the interdecadal mode when the SST over both equatorial eastern Pacific as well as that over the equatorial IO are above normal (Fig.7b)? To understand this, we must remember that the Indian summer monsoon ISO is a manifestation of fluctuations of convection over the two preferred positions, one over the equatorial eastern IO and the other over the MT. This results in a bimodal meridional structure of the dominant ISO mode in outgoing long wave radiation (OLR) or in vertical velocity (see Goswami and Ajayamohan (2001b)). Persistent warmer than normal SST over the equatorial IO leads to persistently enhanced convection and ISO activity in the equatorial IO. Enhanced convection over the equatorial IO gives rise to subsidence over the MT region and leads to suppression of convection and ISO activity over the MT region. Rajeevan *et al.* (2000) indeed show that the recent warm interdecadal phase of the ENSO (the post-1975 period) is associated with an increase in low cloud amount in the equatorial IO and a decrease of the same over the north Bay of Bengal. This bimodal meridional structure of ISO activity on interdecadal time scale is seen in the first EOF of LP filtered ISOV of vertical velocity at 500 hPa (Fig. 15). This pattern of interdecadal variability of ISO activity is quite similar to the SVD pattern of Zveryaev (2002). Following the same argument, we may also expect even the synoptic activity to show a similar interdecadal variability. The frequency of occurrence of monsoon depressions and storms in the north Bay of Bengal has indeed changed from above normal during pre-1970s to below normal during post-1970s (Rajeevan *et al.*, 2000).

6. Decadal Changes in Monsoon Predictability

Significant modulation of the background mean flow (Section 5) and ISO activity (Section 6) on interdecadal time scale indicates that the predictability of the Indian summer monsoon may also undergo interdecadal variability. Foundation for this conjecture lies in the realization that the predictability of the Indian monsoon depends on relative contribution of (or ratio between) slowly varying external forcing and the internal low frequency (LF) variability to the ob-served IAV of the monsoon (Charney and Shukla, 1981; Goswami, 1998; Ajaya Mohan and Goswami, 2003). The internal LF variability of the Indian summer monsoon essentially arise from the summer monsoon ISOs (Ajayamohan and Goswami, 2003) while the interdecadal variability of the background mean flow would modulate the external contribution. Following AjayaMohan and Goswami (2003), estimates of the variance associated with the external and internal components of IAV of zonal winds and relative vorticity at 850 hPa and vertical velocity at 500 hPa during June-September were made from daily NCEP/NCAR reanalysis and a predictability index, F is defined as the ratio between the external and internal variances (Goswami, 2004b). In order to see the variation of the predictability index (F), a 11-year moving window is used starting from 1948 so that the first F value corresponds to 1953. The variation of the predictability index (F) for zonal winds and relative vorticity at 850 hPa averaged over the Indian summer monsoon region (40°E-100°E, 10°N-35°N) is shown in Fig.16a together with the PC1 of the interdecadal mode (Fig. 9c). The correlation between PC1 and F for relative vorticity and zonal winds are -0.88 and -0.84 respectively. In order to contrast the variation of predictability over the

Indian monsoon region with that over the centre of ENSO activity (equatorial central and eastern Pacific), F for relative vorticity at 850 hPa averaged over (170°E-110°W, 10°S-10°N) and F for vertical pressure velocity at 500 hPa averaged over (170°E-110°W, 5°S-5°N) are shown in Fig.16b together with the PC1 of the interdecadal mode (Fig. 9). The correlation between PC1 and F for relative vorticity and vertical velocity over the central and eastern Pacific are 0.89 and 0.82 respectively. Consistent with findings in some earlier studies (Shukla, 1998; AjayaMohan and Goswami, 2003), the climate over the central and eastern Pacific is highly predictable (F much larger than one) while the Indian summer monsoon climate is only marginally predictable (F only slightly larger than one) where the contribution of internal LF variability is comparable in amplitude to that from the external slowly varying forcing. The other interesting point to note from Fig.16 is the following. While the predictability over the central and eastern Pacific is increasing almost monotonically, the value of F in recent years reaching almost double its value during early 1950s, the predictability of the Indian monsoon has decreased significantly during the recent warm phase of the interdecadal ENSO compared to the pre-1970 s colder phase. Strong correlation between PC1 of the interdecadal mode and the predictability over the central and eastern Pacific as well as that over the Indian summer monsoon indicates that the interdecadal variability of predictability over both the regions is strongly linked with interdecadal changes in the background mean flow and intraseasonal activity over the two regions. The internal variability is related to the ISO activity. Compared to the decades between 1950 and 1970, while the ISO activity during the recent decades has decreased over the Asian monsoon region (Fig.15a), it has increased over the equatorial central Pacific (Fig.16c). Resulting decrease in internal variability over the Asian monsoon region should have helped enhance the predictability over the region during the recent years. The observed decrease in predictability of the Asian summer monsoon during the recent decades (Fig.16a) is essentially due to a much larger decrease in external variability in the recent decades due to modulation of the mean circulation by the interdecadal mode (Fig.3, Goswami (2004b)).

7. Discussions and Conclusions

Epochal amplitude modulation of the Indian monsoon with approximately three decades of below normal seasonal mean rainfall followed by approximately three decades of above normal seasonal mean rainfall has been known for a while. Physical mechanisms responsible for this interdecadal variability are poorly understood. Some studies (Mehta and Lau, 1997; Agnihotri *et al.*, 2002) indicate a possibility of forcing the quasi-60 year variability of the monsoon by solar forcing variability at the same time scales. Temporal record of total solar irradiance (TSI) has been reconstructed since 1610 based on parameterization of sunspot darkening and facular brightening (Lean *et al.*, 1995). Recently, the TSI reconstruction has been extended to 843 AD based on a quantitative estimate of common variations of production rates of ^{14}C and ^{10}Be (Bard *et al.*, 2000). While, spectral analysis of TSI derived from sunspot numbers do show a significant peak with periodicity of 53 years (see Agnihotri *et al.* (2002)), the TSI data derived from ^{14}C and ^{10}Be show significant peaks only at periods longer than 100 years. Therefore, existence of a significant oscillation of the solar flux at 50-60 year time scale itself needs to be established beyond reasonable doubt. Moreover, the absolute changes in solar intensity on interdecadal time scale is very small. Hence, the direct forcing by solar flux changes on climate in general and Indian monsoon in particular on interdecadal time scale is not well established. Some evidence is presented here to support an alternative hypothesis that the interdecadal variability of the monsoon is manifestation of a global coupled ocean-atmosphere mode of variability. It is shown that the interdecadal variability of the ENSO (amplitude modulation mode) is strongly negatively correlated with the interdecadal variability of the Indian summer monsoon. Using long records of Indian monsoon rainfall, global SST and SLP data, it is shown that interdecadal variability of both AIR and ENSO (Nino3 SST) are associated with almost identical global pattern of SST and SLP. Thus, the interdecadal variability of the Indian monsoon and that of the ENSO are likely to be parts of a global scale oscillation on quasi-60 year time scale. Schlesinger and Ramankutty (1994) found that there exists a 65-70 year oscillation of the global surface temperature. Using a fully coupled ocean-atmosphere model, Delworth *et al.* (1993) showed ocean-atmosphere interaction can indeed give rise to a climatic oscillation with period of approximately 50 years. These findings support our hypothesis that the quasi-60 year oscillation of the Asian monsoon and ENSO is manifestation of a global coupled ocean-atmosphere mode of oscillation. The ENSO is known to have a major interdecadal transition in the mid-seventies with the period between 1950-1977 and that between 1978 and 2002 representing two opposite phases of the interdecadal oscillation. Using NCEP/ NCAR reanalysis data, it is shown that a coherent three dimensional circulation pattern is associated with the interdecadal mode of ENSO variability with a first baroclinic mode vertical structure and a distinct three cell equatorial Walker circulation in the equatorial region. It is also found that the anomalies of the MH and Walker circulation associated with the interdecadal variability are comparable in magnitude to those associated with IAV of ENSO. A distinct regional MH circulation associated with the interdecadal mode has significant persistent ascending motion in the equatorial IO between 10 S and 10 N with upper level subsidence over the summer monsoon region. Suppression of convection by the persistent upper level subsidence associated with the interdecadal ENSO mode explains the negative correlation between Indian summer monsoon and ENSO on interdecadal time scale. The three dimensional structure of the MH and Walker circulation associated with the interdecadal mode of variability indicates that the mechanism through which ENSO influences Indian monsoon on interannual time scale also operates on interdecadal time scale. Strong association between variation of precipitation and low level winds and first baroclinic vertical structure of wind fields associated with it indicates that the interdecadal mode of variability is strongly convectively coupled. The following positive feedback between the atmosphere and the ocean may be envisaged for generating the interdecadal mode of variability. Enhanced precipitation over northern south America and Indonesia (Fig.10b) gives rise to low level convergence and weakens the easterlies in the eastern Pacific and southeastern equatorial IO. Decrease of LH flux associated with the weakened mean winds lead to positive net heat flux to the ocean in the eastern Pacific and eastern IO leading to positive SST anomalies in these regions (Fig.10a). Higher SST in these regions further weaken the easterlies and lead to further increase in SST. However, the exact mechanism for controlling this positive feedback and leading to an oscillatory behavior is not quite clear. More analysis and modeling studies are required to better understand the air-sea interaction associated with this mode. In these attempts to gain insight regarding the interdecadal variability of the ENSO-monsoon relationship through examination of the three dimensional structure of the interdecadal variability, precipitation and vertical pressure velocity from NCEP/NCAR reanalysis project have been used. As precipitation is not an assimilated variable, it is influenced by physical parameterizations of the model used in the analysis system. As a result, a certain amount of concern has been raised (Kinter *et al.*, 2004) for use of precipitation (and also vertical velocity as it is forced by precipitation) from NCEP/NCAR reanalysis for study of interdecadal variability. This is a genuine concern. However, low level horizontal winds from NCEP/NCAR reanalysis are assimilated variables and are more reliable. The consistency between the low level convergence and the precipitation anomalies for the interdecadal mode (Fig.8b,c) indicates that the large scale pattern of interdecadal variability of precipitation is probably still reasonable in NCEP/NCAR reanalysis. However, it may not be useful to compare interdecadal variability of precipitation from NCEP/NCAR reanalysis at small locations such as a station. Intraseasonal oscillations in the tropics arise from interaction between convection and dynamics which in turn depends on the background mean flow. It is shown that the modulation of large scale mean flow on interdecadal time scale is associated with modulation of intraseasonal activity in the tropics. The cold (warm) interdecadal phase during pre-1970s (post-1970s) is shown to be associated with decrease (increase) in ISO activity over equatorial central Pacific and IO but increase (decrease) in ISO activity over the Indian summer monsoon region. Increase in ISO activity over central and eastern Pacific and equatorial IO associated with warm interdecadal phase is consistent with systematically higher SST in these regions. This is also consistent with decrease in ISO activity over the Indian summer monsoon region as increase in convection over the equatorial IO leads to suppression of convection and hence ISO activity over the summer monsoon region. As the predictability of the monthly mean and seasonal mean climate in the tropics is determined by relative contribution of external forcing (slow modulation of the mean) and internal LF oscillations (primarily arising from ISO activity), it is also expected to be modulated by the interdecadal oscillation. It is shown that the Indian summer monsoon predictability has gone down significantly during the warm interdecadal phase of post-1970 s compared to the cold interdecadal phase of pre-1970s. This is in contrast to the climate over the central Pacific where the predictability has increased significantly from pre-1970s to post-1970s. Increase of predictability over the core ENSO region in the Pacific and decrease of the same over the Indian monsoon region during the post 1970s is strongly correlated with increase and decrease of ISOV in the two regions during the phase of interdecadal variability.

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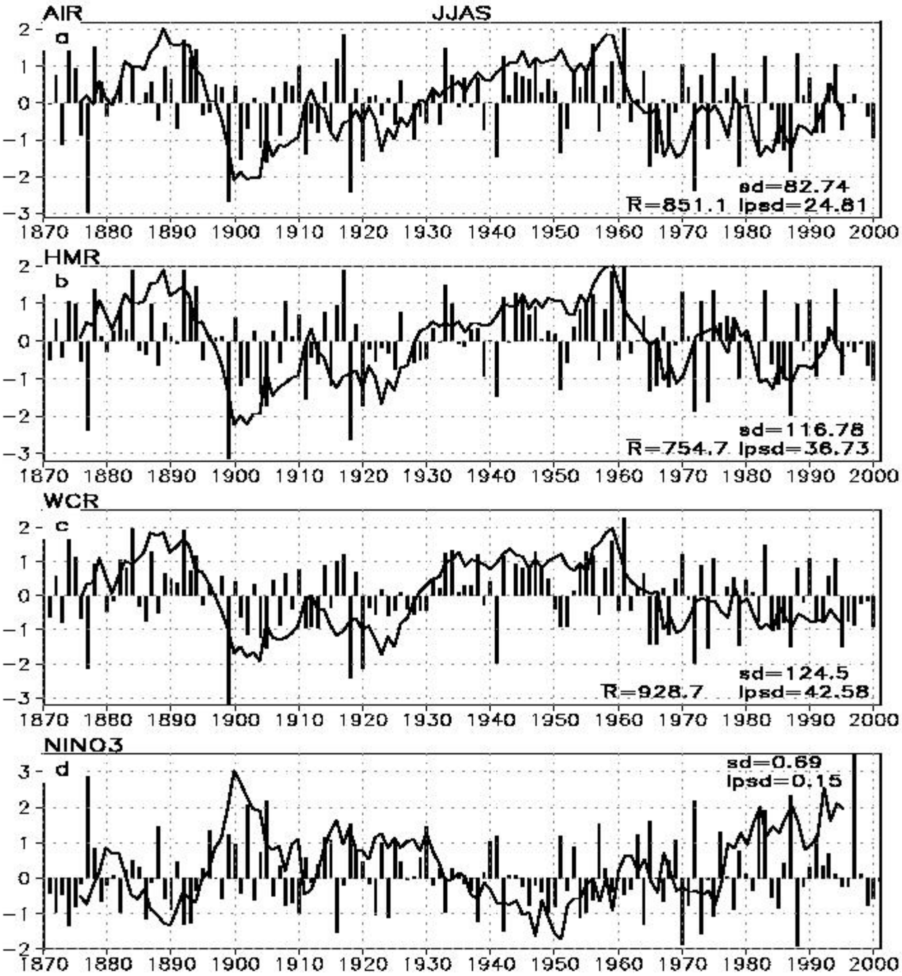

Figure 1: Interannual (bar) and interdecadal (solid) variability of three Indian summer (JJAS) rainfall indices (a-c) and summer (JJAS) SST over Nino3 (170°W-90°W, 5°S-5°N). (a) All India rainfall (AIR), (b) Homogeneous monsoon region rainfall (HMR), (c) West-central India rainfall (WCR). LP filtered seasonal anomalies are obtained by using a 11-year running mean. For the rainfall time series, long term mean seasonal rainfall ($\bar{R}$), interannual standard deviation (sd) and standard deviation of the LP filtered seasonal anomalies (lpsd) are shown (in millimeter). Interannual as well as LP filtered anomalies are normalized by their own standard deviations.

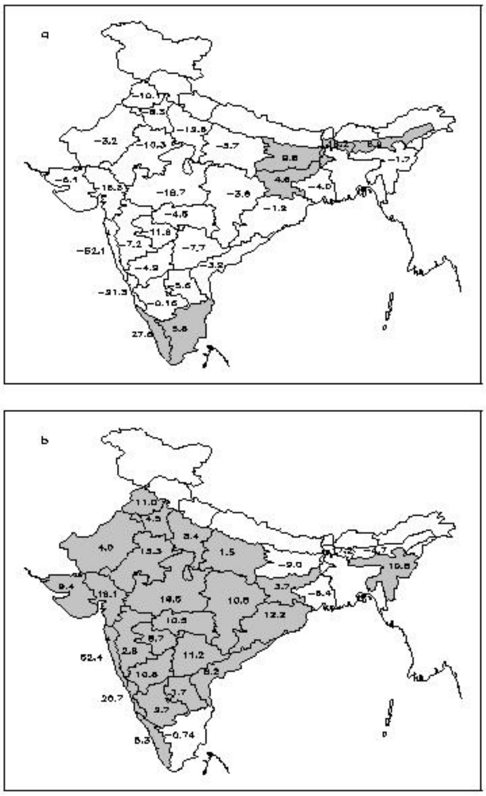

Figure 2: Spatial distribution of rainfall anomalies within the Indian continent during two contrasting interdecadal epochs. June-September rainfall anomaly (mm) over individual meteorological sub-divisions of India averaged over (a) a below normal epoch, 1900- 1925 and (b) an above normal epoch, 1940- 1965. Positive anomalies are shaded.

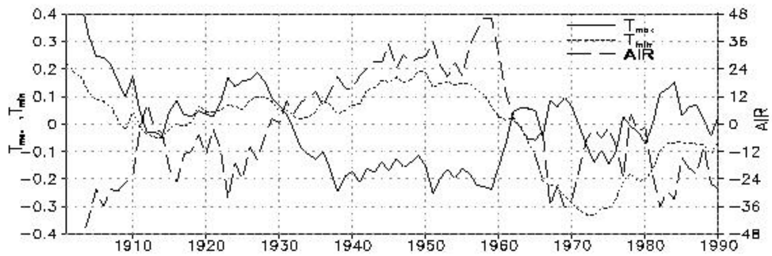

Figure 3: Interdecadal variation of June-September maximum surface temperature (Tmax) and minimum surface temperature (Tmin) over India in K (scale on left) together with that for AIR (mm, scale on right).

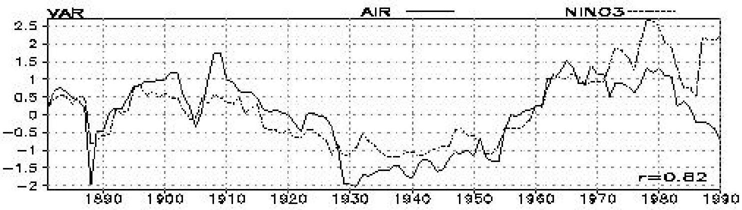

Figure 4: Interdecadal variability of interannual variance of normalized AIR (solid) and JJAS Nino3 SST(dotted) using a 15-year moving window. The correlation (r) between the two is shown.

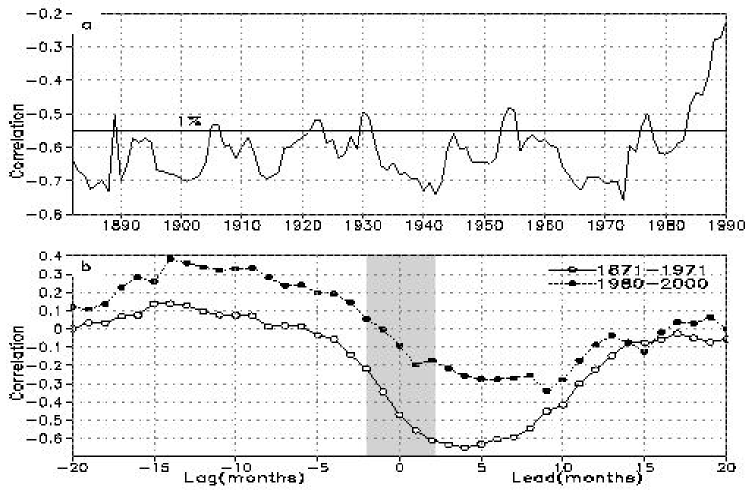

Figure 5: (a) 21-year moving correlation between AIR and JJAS Nino3 SST, the horizontal line representing significance at 1 percent level. (b) Lag-correlations between AIR and monthly mean SST anomalies over the Nino3 region using data between 1871 and 1971 (open circle) and the recent period between 1980 and 2000 (filled circle).

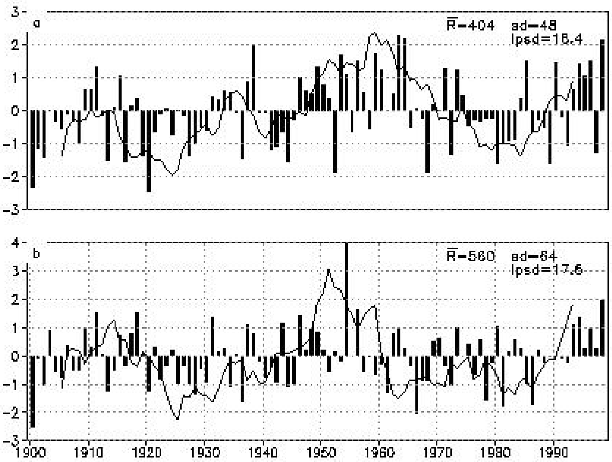

Figure 6: Interannual (bar) and interdecadal (solid) variability of east Asian summer monsoon (May-August) rainfall over two areas in China. (a) North-eastern China between 37.5°N - 47.5°N, 112.5°E-125.0°E , (b) Yangtze River Valley between 27.5°N - 37.5°N, 105.5°E-115.0°E. LP filtered seasonal anomalies are obtained by using a 11-year running mean. The long term mean seasonal rainfall ($\bar{R}$), interannual standard deviation (sd) and standard deviation of the LP filtered seasonal anomalies (lpsd) are shown (in millimeter). Interannual as well as LP filtered anomalies are normalized by their own standard deviations.

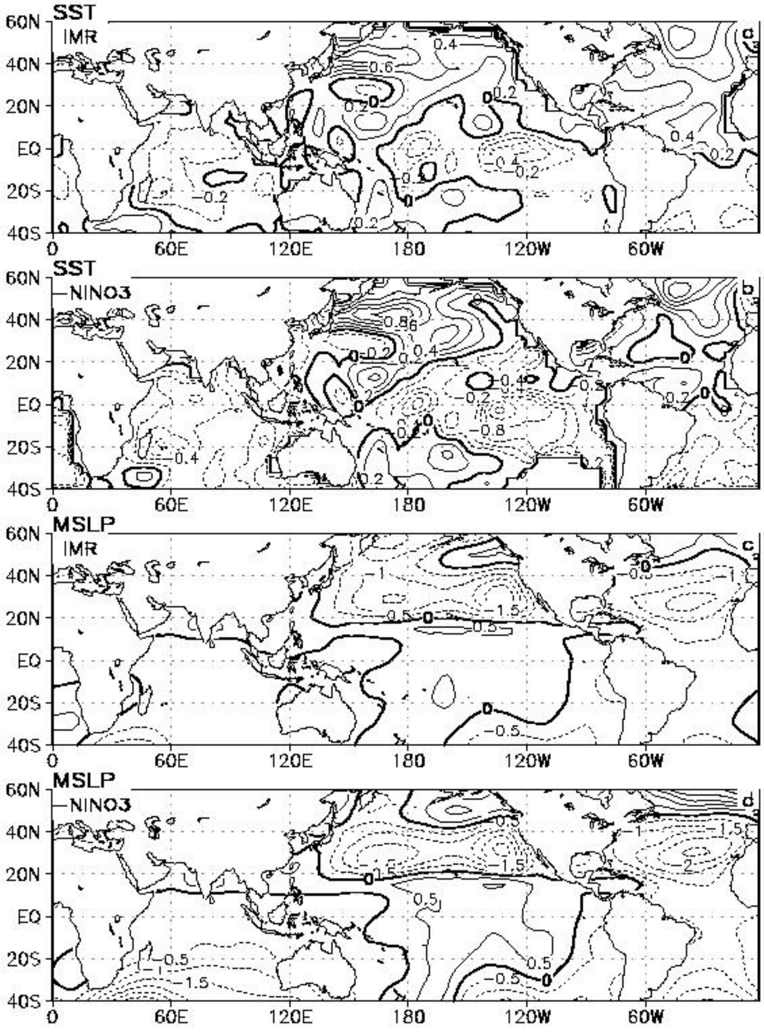

Figure 7: Spatial pattern obtained by regressing global SST (top two panels) and global SLP (bottom two panels) on LP filtered AIR and -Nino3 (shown in Fig.1) respectively. Negative contours are dashed and contour interval is 0.1 K per standard deviation for SST and 0.1 hPa for SLP respectively.

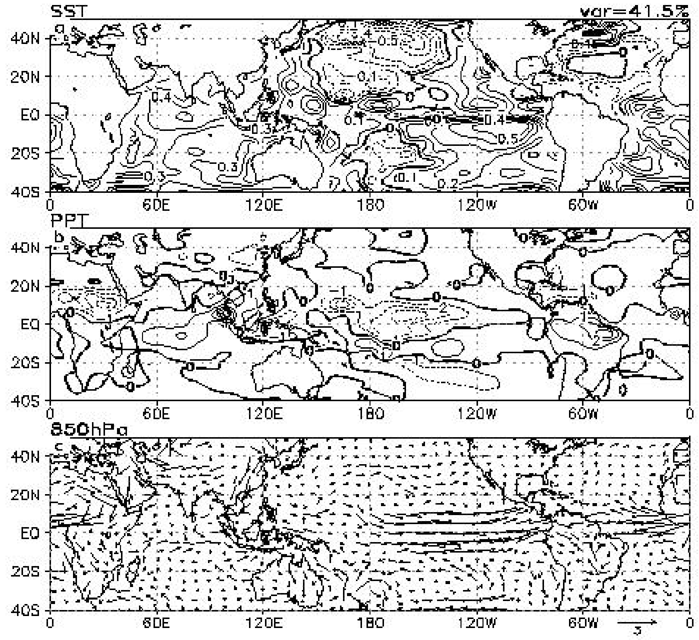

Figure 8: Spatial pattern of the first combined EOF (CEOF) of LP filtered fields (a) SST (K), (b) precipitation ($mmday^{-1}$) and (c) vector winds at 850 hPa (ms^{-1}). Scale for the vector winds is shown.

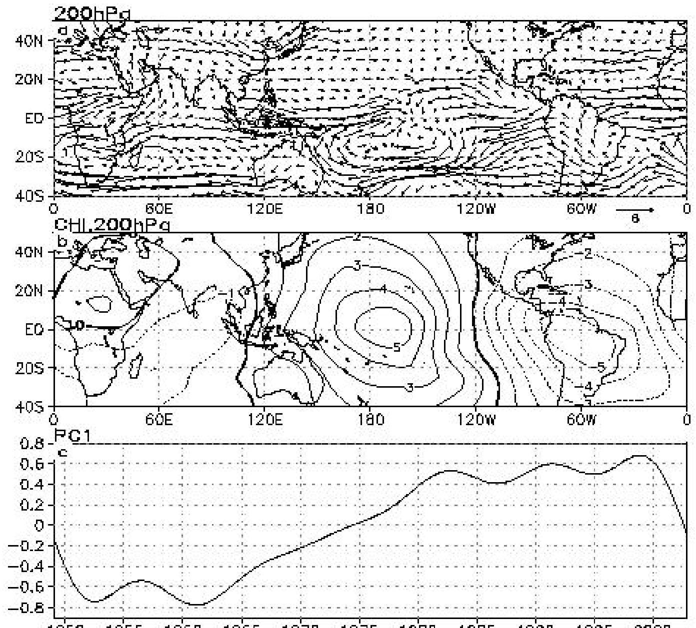

Figure 9: Continuation of spatial pattern of the first CEOF of LP filtered fields (a) vector winds at 200 hPa (ms^{-1}). Scale for the vector winds is shown. (b) Velocity potential at 200 hPa ($10^{6}\ s^{-1}$) and (c) Time evolution of the Principal Component for CEOF1 (PC1) in arbitrary unit.

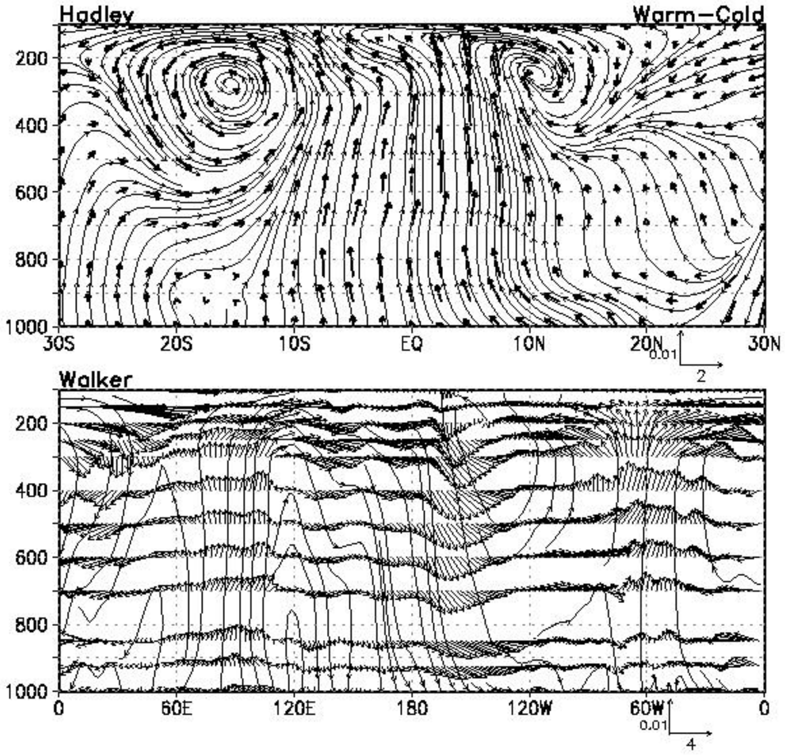

Figure 10: Monsoon Hadley (MH) and equatorial Walker circulation associated with the interdecadal mode. (top) Latitude-height section of meridional winds (ms^{-1}) and negative of vertical pressure velocity (Pas^{-1}) averaged over 70°E-110°E of warm minus cold composite of LP filtered fields at 12 vertical levels. Warm (cold) composite was created by averaging LP filtered fields between January 1952 and December 1965 (January 1982 and December 1995) . (bottom) Longitude-height section of zonal winds (ms^{-1}) and negative of vertical pressure velocity (Pas^{-1}) averaged over 10°S-10°N of warm minus cold composite of LP filtered fields at 12 vertical levels. Unit vector in the vertical direction is 0.01 Pas^{-1} and 2 and 4 ms^{-1} for the top and bottom panels respectively.

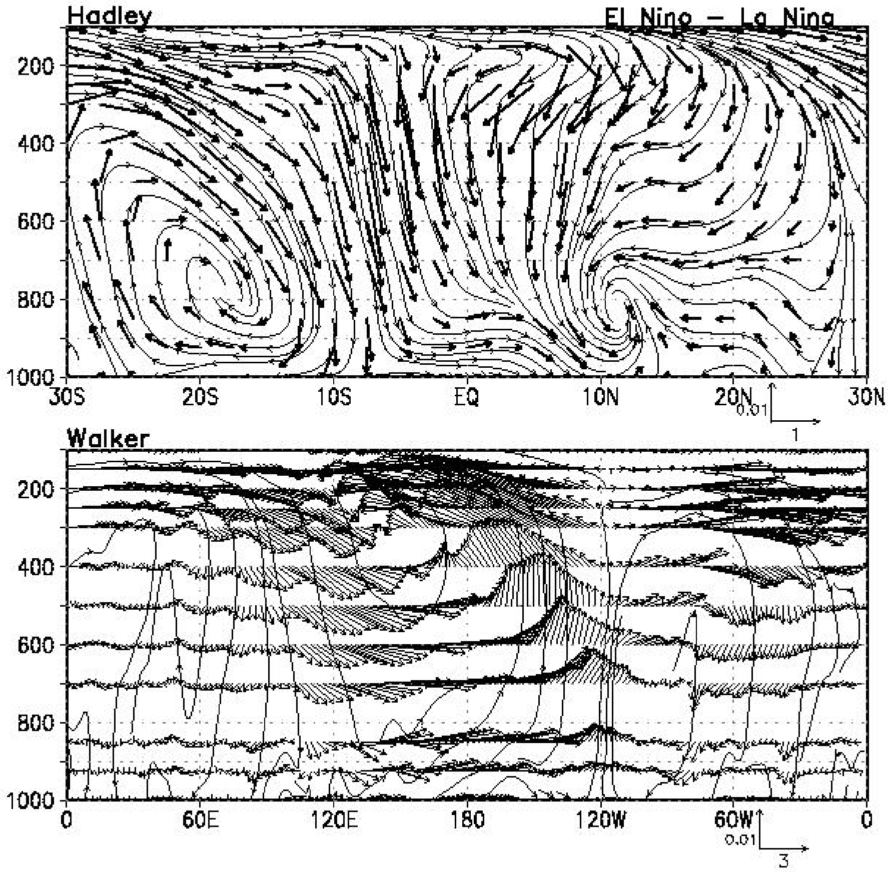

Figure 11: Monsoon Hadley (MH) and equatorial Walker circulation associated with the interannual ENSO mode during northern summer (JJAS). (top) Latitude-height section of meridional winds (ms^{-1}) and negative of vertical pressure velocity (Pas^{-1}) averaged over 70°E-110°E of El Nino minus La Nina composite of residual (interannual) anomaly fields at 12 vertical levels. El Nino (La Nina) composite was created by averaging JJAS anomalies for the years 1957, 1965, 1972, 1976, 1982, 1983, 1987, 1997 (1964, 1970, 1973, 1988). (bottom) Longitude height section of zonal winds (ms^{-1}) and negative of vertical pressure velocity (Pas^{-1}) averaged over 10°S-10°N of El Nino minus La Nina composite of residual (interannual) anomaly fields at 12 vertical levels. Unit vector in the vertical direction is 0.01 Pas^{-1} and 1 and 3 ms^{-1} for the top and bottom panels respectively.

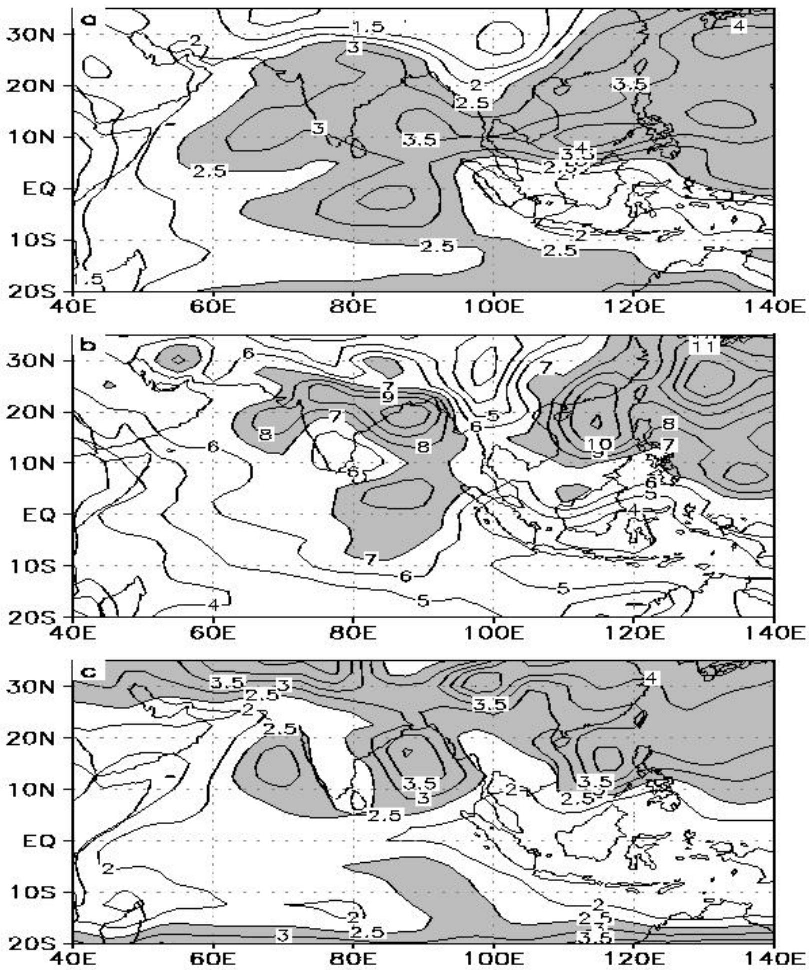

Figure 12: Climatological mean (based on 55 years) ISO activity during northern summer (1 June – 30 September). (a) Climatological mean of standard deviation of 10-90 day filtered zonal winds at 850 hPa (ms^{-1}). (b) Climatological mean of standard deviation of 10-90 day filtered relative vorticity at 850 hPa ($10^{-6}s^{-1}$). (c) Climatological mean of standard deviation of 10-90 day filtered vertical pressure velocity at 500 hPa ($0.01Pas^{-1}$).

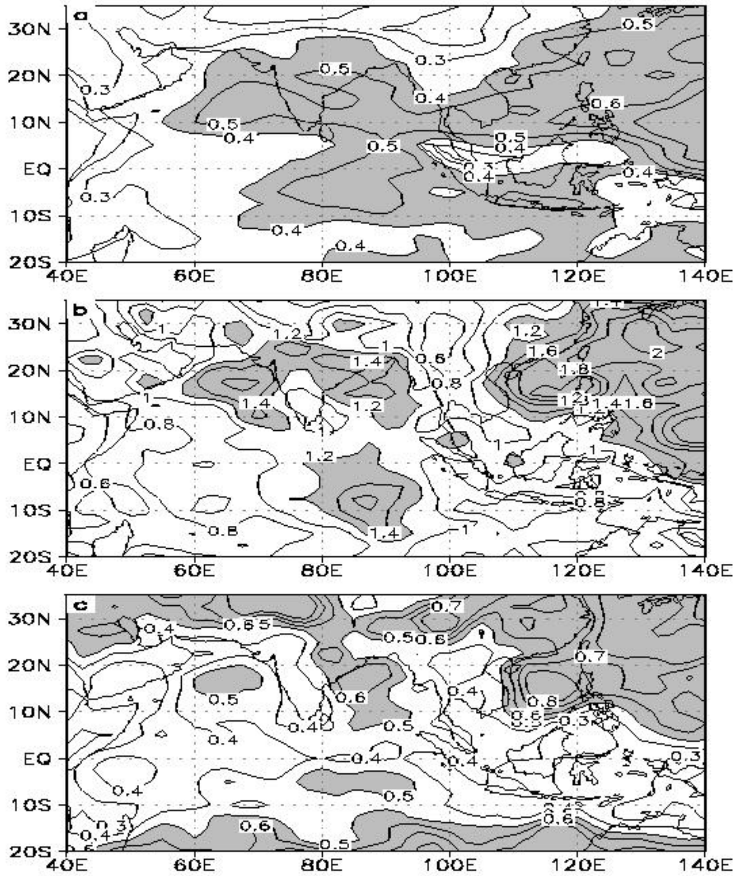

Figure 13: Amplitude of IAV of ISO activity. Interannual standard deviation of amplitude of 10-90 day filtered anomalies during 1June-30 September of (a) zonal winds at 850 hPa (ms^{-1}) , (b) relative vorticity at 850 hPa $10^{-6}s^{-1}$, (c) vertical pressure velocity at 500 hPa ($0.01Pas^{-1}$).

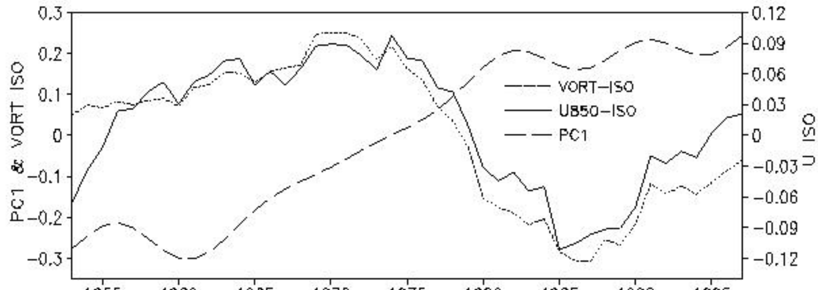

Figure 14: LP filtered (11-year running mean) interannual standard deviation of ISO activity averaged over 40°E-100°E, 10°N-35°N of zonal winds at 850 hPa (solid) and relative vorticity at 850 hPa (dotted) together with PC1 of the interdecadal mode (dashed) scaled down by a factor of 5.1. Unit for standard deviation of zonal winds is ms^{-1} while that for relative vorticity is $10^{-6}s^{-1}$.

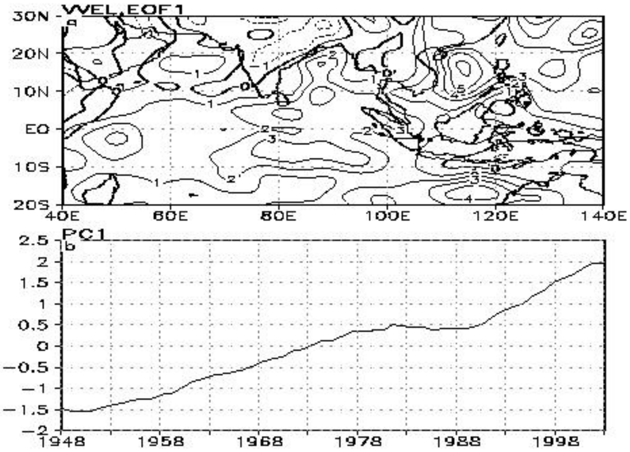

Figure 15: Spatial pattern of first EOF LP filtered vertical pressure velocity at 500 hPa (Pas^{-1}) and time evolution of the PC1.

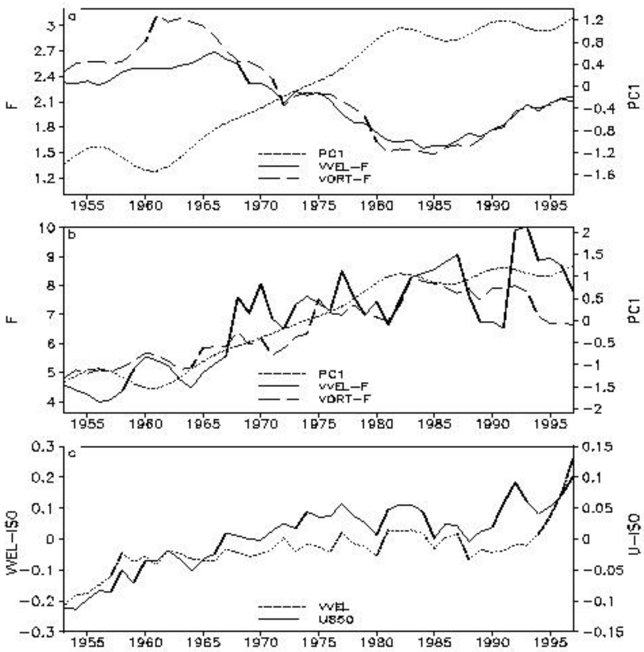

Figure 16: (a) Variation of predictability index (F) of relative vorticity at 850 hPa and vertical pressure velocity at 500 hPa averaged over the Indian summer monsoon region (40°E-100°E, 10°N-35°N) based on a 11-year moving window together with PC1 of the interdecadal mode. (b) Variation of predictability index (F) of relative vorticity at 850 hPa and vertical pressure velocity at 500 hPa averaged over the central Pacific (160°E-160°W, 10°S-10°N) based on a 11-year moving window together with PC1 of the interdecadal mode. (c) 11-year running mean of ISO activity of zonal winds at 850 hPa and vertical pressure velocity at 500 hPa over the central Pacific (160°E-160°W, 10°S-10°N).